Changes in electrical conductivity of liquid foods during ohmic heating

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Abstract: Ohmic heating is a food processing method in which alternating current (AC) went through a food sample and resulted in internal energy generation in foods. It is an alternative fast heating technique. Its principal advantage is the ability to rapidly and uniformly heat food materials of various densities. During ohmic heating, change in electrical conductivity was observed. The intensity of food materials' electrical conductivity or overall resistance critically controls ohmic heating rate. An ohmic heating set-up was prepared under this project. Tomato juice was heated (about 32℃ to 80℃) in a batch type ohmic heater at different voltage gradients in the range of 50–70 V/cm. It was statistically found that the voltage gradient had significant impact on conductivity and system performance coefficient (SPC) (P<0.05). It was concluded that the electrical conductivity values linearly increased with temperature. The SPCs of the system ranged between 0.779 and 0.943. The value of R^2 of the linear model was greater than 0.98.

Keywords: ohmic heating, electrical conductivity, thermal conductivity, liquid foods

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1 Introduction

Conventional heating processes essentially consist of heat-transfer mechanisms of conduction, convection and radiation. The internal resistance by conduction results in very heterogonous treatment and notable loss of product quality. To overcome these problems, alternative technologies utilizing electrical energy directly in food processing have attracted interests in the food industry in recent decades. Ohmic heating technology has become attractive in the past few years due to availability of energy at reasonable cost and improved designs. Ohmic heating occurs when an electric current 'I' passes through a food of resistance 'R' with the resultant energy generation causing temperature rise, just as an electric current heats a hot plate[1,2]. Ohmic heating of food is defined as a process where (primarily alternating) electric currents pass through an electric conductive food directly connected to the electrodes to which sufficient power is supplied. At the same time, heat is produced in the form of internal energy generation within the food. Hence, ohmic heating is sometimes also referred to as Joule heating, electrical resistance heating, direct electric resistance heating, electro-heating or electro conductive heating[3]. This technique involves several advantages like heating of food material by internal heat generation without the limitation of conventional heat transfer and some of the non uniformity commonly associated with microwave

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heating due to limited dielectric penetration. Heating takes place volumetrically and the product does not experience a large temperature gradient within itself as it heats. Higher temperature in particulates than liquid can be achieved which is impossible for conventional heating, reducing risks of fouling on heat transfer surface and burning of food product, resulting in minimal mechanical damage and better nutrient and vitamin retention. It has high energy efficiency because 90% of electrical energy is converted into heat. The method optimizes capital investment and product safety as a result of high solids loading capacity. Its process control is fairly easy due to instant switch-on and shut down. Since it does not contain moving parts, the maintenance cost is low. The system can be stored and distributed in ambient temperature when confined with an aseptic filling system. It does not create any noise and is environment friendly[4]. Similarly, ohmic heating was found to be more efficient for the required microbial and pectin esterase inactivation due to a shorter residence time while released flavor compounds were not degraded as quickly as during conventional pasteurization [5].

The main critical factor in ohmic heating is the electrical conductivity. Electrical conductivity is the measure of how well a substance transmits electrical charge. In ohmic heating terminology, the electrical conductivity is a measure of the mineral or ionic content. Therefore, it is very important to determine the electrical conductivity of the food product in the ohmic heating process because it measures the suitability of the product for ohmic heating. The aim of this study was to obtain electrical conductivity data for tomato juice during ohmic heating over the sterilization temperatures range. Effects of temperature and voltage gradients on ohmic heating rates of tomato juice were studied. Ohmic heating of tomato juice as a single phase was also mathematically modeled by taking the system performance coefficients into account.

2 Materials and methods

2.1 Sample preparation

The fresh tomato fruits were purchased from a local market in Anand, Gujarat. Prior to experiments, these tomatoes were stored at refrigeration conditions (about 4°C) for no more than 8 hours. During experiments, fruits were washed with normal water to remove dirt and other impurities from the skin and then the water was drained. Free water on the surface was also removed by putting the tomatoes on the blotting paper. For experiment, the fruits were crushed into a mixture and filtered with No.9 mesh filter.

2.2 Ohmic heating system

An ohmic heating chamber of 500 mL capacity was fabricated at 20 cm in length and 6 cm in inner diameter. An internally male adapter the external diameter of which is the same as that of the internal diameter of the pipe, with anti-leakage rubber gasket, is fitted with the glass pipe. An internally threaded PVC cap plug is fitted on the male adapter. Provisions are given to fix the thermocouple along the length of the pipe and also in each of the screw caps to fix the electrodes. A hole with diameter of 2.5 cm was created at the top of the cell to observe bubble formation and exit of vapor in the cell.

2.3 Electrodes and thermocouple

The surface of the food grade SS 304 electrodes (D=5.6 cm) is polished to become smooth using fine emery sheet. Polished electrode plates of 1.5 mm thick are fixed closely adjacent to the end of the screw caps of the ohmic heating chamber using bolts and nuts. A hole of 0.6 cm is drilled on the centre end side to fasten the elctrodes with the chamber using bolts and nuts. The themocouple used for the experiment was the "K" type (Chromel-Alumel for the range of 40-500℃). Figure 1 shows different parts of electrodes of the ohmic heater and Figure 2 shows the thermocouple positioning.

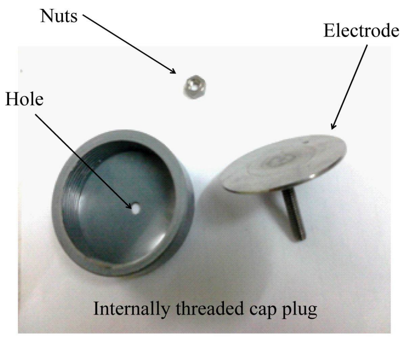

Figure 1 Electrodes of ohmic heater

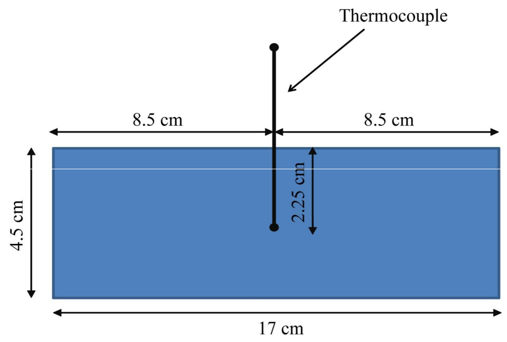

Figure 2 Thermocouple positioning

2.4 Power source

Power from domestic supply (220 V, 50 Hz) was used. Voltage was supplied to the electrodes at the end sides. Digital ammeter was used to measure the amount of current in amperes. It displayed the output on an electronic display and was more precise and more effective than the analogue substitutes. It also provided readings up to many decimal places, which offered greater accuracy. It had positive and negative leads built into them and it had very low resistance which was usually almost negligible so that accurate readings could be acquired. Figure 3 shows the experimental setup of ohmic heating. The detailed specifications are given in Table 1.

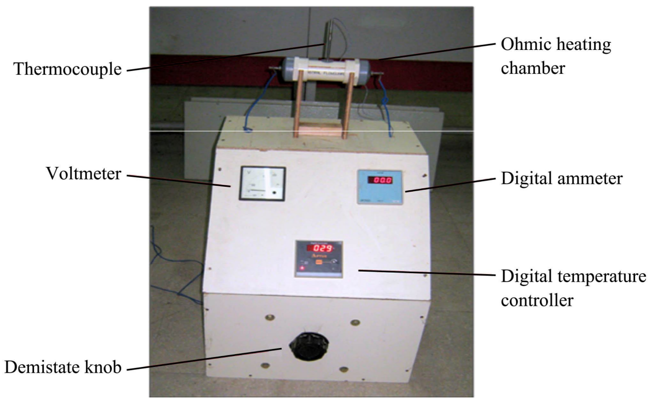

Figure 3 Experimental setup

Table 1 Technical specifications of the ohmic heating chamber

Items	Value
Distance between electrodes (m)	0.17
Effective diameter of the electrode (m)	0.045
Area of the electrodes (m²)	1.5896×10^{-3}
Volume of the chamber (mL)	500

2.5 Accuracy

To check the accuracy of the ohmic system, it was compared and calibrated with the standard conductivity. The calibration results for the accuracy of electrical conductivity of 0.1 M NaCl solution revealed that there was no significant difference between standard electrical conductivity of 0.1 M NaCl solution and the experiment data. The electrodes were thoroughly rinsed and dematerialized with twice-distilled water after each run[6,7].

2.6 Measurement of electrical conductivity

It is well known that when electrolytes are placed in an electric field, the ions present within the electrolyte move towards the electrodes with opposite charges. The movement of ions in the electrolyte generates heat. Similarly, when an alternating current or any other wave form current passes through the food placed between two electrodes, the food is heated by internal heat generation. Electrical conductivity (S/m) can be calculated from voltage and current data using the following equation:

$$\sigma = \frac{IL}{VA} \tag{1}$$

2.7 Mathematical model

The ohmic heating system performance coefficients (SPCs) were defined by using the energies given to the system and taken up by the juice samples. To simplify the calculation of SPC, the following assumptions were made: (i) specific heat capacity of the tomato juice is constant within the range of temperatures considered; (ii) SPC is constant, (iii) Prior to commencing ohmic heating it is assumed that the entire sample is at a uniform temperature of about 32℃. The energy given to the system during ohmic processing in unsteady state heat will be equal to the energy required to heat the sample plus the energy loss[8,9].

$$P = Q + E_{loss} \tag{2}$$

$$\Sigma(VIt) = mCp(T_f - T_i) + E_{loss} \tag{3}$$

System performance coefficient (SPC) was defined as:

$$SPC = \frac{Q}{P} \tag{4}$$

The energy loss is the sum of the heat required to heat up the test cell, the heat loss to the surroundings by natural convection, the heat loss for physical, chemical and electrochemical changes of juice, and the electrical energy which has not been converted into heat. The energy loss calculations for the experimental data were performed by using the method in references [9,10]. The physical properties used in the computations and the experimental parameters are given in Table 2.

Table 2 Properties of tomato juice used in calculations

Property	Value
Density (kg/m^3)	1079.36
Specific heat (J/kg·°C)	3719

3 Results and discussion

3.1 Effect of temperature and voltage gradient

The changes in electrical conductivity of tomato juice with temperature during ohmic heating at three different voltage gradients are given in Figure 4. Electrical conductivity increased as the temperature increased during ohmic heating. When biological tissue is heated, it's electrical conductivity increases due to increase in the ionic mobility. This phenomenon occurs because of structural changes in the tissue like cell wall protopectin breakdown, expulsion of non conductive gas bubbles, softening, and lowering in aqueous phase viscosity. Bubbling was observed as the temperature increases, especially at high voltage gradients[11]. It was observed that electrical conductivities sharply increased with temperature rise after bubbling started due to formation of electrolytic hydrogen bubble as fruit juices are acidic. One way analysis of variance were used for statistical analysis and showed that voltage gradient had a significant effect (p<0.05) on the electrical conductivity of tomato juice.

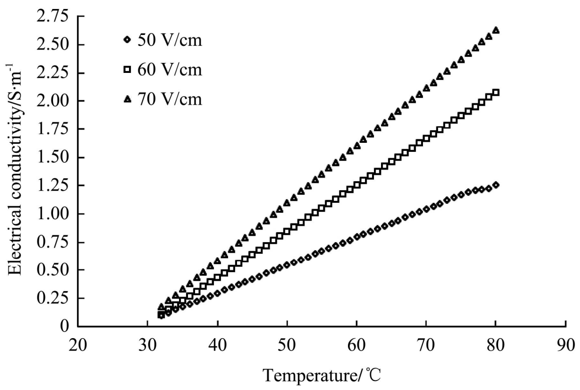

Figure 4 Electrical conductivity of tomato juice during ohmic heating at different voltage gradients

Several researchers reported that the increase in the electrical conductivity values with temperature has been explained by reduced drag of ion movement. Results of this study were similar to those reported by some references[6-10,12-19]. The highest electrical conductivity was observed on 70 V/cm, followed by 60 and 50 V/cm. The electrical conductivity at 60 V/cm was slightly higher than that at 50 V/cm. Similar observations were reported for grape juice[6-8]. Between 55 and 75℃, the electrical conductivity at 40 V/cm was slightly higher than that at 20 or 30 V/cm. The values of electrical conductivity are comparable with the reported values of 0.1–1.6 S/m mentioned for apple and sour cherry juices at 20–60 V/cm and 30–75℃ [10].

Since the experimental electrical conductivity results for the tomato juice samples given in Figure 4 showed a linear trend with increasing temperature, a linear equation shown in equation (5) was used to fit the experimental data. The constants and the linear regression coefficients are given in Table 3.

$$\sigma = ZT + C \tag{5}$$

Table 3 Parameters of the linear model of tomato juice during ohmic heating

Voltage gradient/V·cm^{-1}	B	C	R^2
70	0.051	-1.454	0.99
60	0.041	- 1.205	0.98
50	0.024	- 0.687	0.99

3.2 System performance coefficient (SPC)

The electrical energies given to the system, the heat taken by the tomato juice, performance coefficients and heating times for mathematical model calculated by the experimental data are shown in Table 4.

Table 4 System performance coefficients for different voltage gradients

V/V·cm^{-1}	Q/J	P/J	SPC	T_i/°C	T_f/°C	t/s
50	8889	9426	0.943	32.0	79.8	51
60	8936	10576	0.845	32.2	80.0	47
70	9087	11671	0.779	32.4	80.2	40

The results indicated that the SPC depended strongly on the voltage gradient applied (p<0.05). For the tomato juice samples the SPC increased from 0.779 to 0.943 as the voltage gradient decreases. At the voltage gradient of 50 V/cm, the SPC was 0.943, which indicated that 6% of the electrical energy given to the system was not used to heat up the test liquid. However, for higher voltage gradients, SPC values were lower and the heat required to heat up the test cell was too small to account for the energy loss term (E_{loss}). Therefore, the system was performing better. The level of agreement between the predicted and experimental heating times was relatively good when these electrical conductivity models were used. A similar observation was reported by for orange juice, peach puree and apricot puree[2,9, 10].

4 Conclusions

The tomato juice was heated in a batch type lab scale ohmic heater by applying voltage gradients in the range of 50–70 V/cm. The electrical conductivity increased linearly with temperature. The electrical conductivity of tomato juice is strongly dependent on temperature. The rate of change of the electrical conductivity of tomato juice with temperature for 70 V/cm was higher compared to other voltage gradients applied. As the voltage gradient increased, time and performance coefficient decreased. The voltage gradient was statistically significant on the ohmic electrical conductivity and SPCs. The results showed that the linear model was found to be the most suitable model for describing the electrical conductivity curve of the ohmic heating process of tomato juice.

Nomenclature

σ	Electrical conductivity (S/m)
I	Current intensity (A)
V	Voltage (V)
L	Gap between the electrodes (m)
A	Electrode surface area (m^2)
P	Electrical energy given to the system (J)
Q	Energy required to heat the sample (J)
E_{loss}	Energy loss (J)
t	Time (s)
m	Mass of the sample (kg)
C_P	Specific heat capacity (J/kg$^\circ$C)
T_f	Final temperature ($^\circ$C)
T_i	Initial temperature ($^\circ$C)
T	Temperature ($^\circ$C)
B and C	Constants

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